The Red-Sequence Cluster Survey: first lensing results

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Abstract. The Red-Sequence Cluster Survey (RCS) is a 100 deg^2 galaxy cluster survey designed to provide a large sample of optically selected clusters of galaxies with redshifts $0.1 < z < 1.4$. The survey data are also useful for a variety of lensing studies. Several strong lensing clusters have been discovered so far, and follow up observations are underway. In these proceedings we present some of the first results of a weak lensing analysis based on ~ 24 deg^2 of data. We have detected the lensing signal induced by intervening large scale structure (cosmic shear) at high significance, and find $\sigma_8 = 0.81^{+0.14}_{-0.19}$ (95% confidence; for a CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$). Another application of these data is the study of the average properties of dark matter halos surrounding galaxies. We study the lensing signal from intermediate redshift galaxies with $19.5 < R_C < 21$ using a parametrized mass model for the galaxy mass distribution. The analysis yields a mass weighted velocity dispersion of $\langle\sigma^2\rangle^{1/2} = 111 \pm 5$ km/s. In addition we have constrained for the first time the extent of dark matter halos, and find a robust upper limit for the truncation parameter $s < 470h^{-1}$ kpc (99.7% confidence). The biasing properties of these galaxies as a function of scale are also studied. The RCS data allow us to measure the ratio of the bias parameter b and the galaxy-mass cross-correlation coefficient r. The results are consistent with a scale-independent value of b/r, for which we find $b/r = 1.05^{+0.12}_{-0.10}$ (for a ΛCDM cosmology).

1 Introduction

The Red-Sequence Cluster Survey[1] (e.g., Gladders & Yee 2000) is the largest area, moderately deep imaging survey ever undertaken on 4m class telescopes. The survey comprises 100 square degrees of imaging in 2 filters (22 widely separated patches imaged in R_C and z'). Ten patches have been observed using the CFHT 12k mosaic camera, and the remaining 12 southern patches have been observed using the Mosaic II camera on the CTIO 4m telescope. The depth of the survey (2 magnitudes past M^* at $z = 1$) is sufficient to find a large number of galaxy clusters to $z \sim 1.4$.

The survey allows a variety of studies, such as constraining cosmological parameters from the measurement of the evolution of the number density of galaxy clusters as a function of mass and redshift, and studies of the evolution of cluster galaxies, blue fraction, etc. at redshifts for which very limited data are available at present.

The data are also useful for a range of lensing studies. Strong lensing by clusters of galaxies allows a detailed study of their core mass distribution. In addition, given the shallowness of the survey, the arcs are sufficiently bright to be followed up spectroscopically (e.g., Gladders, Yee, & Ellingson 2001). Thanks to the large magnifications of the arcs, it allows unprecedented studies of the properties of high redshift galaxies. Furthermore, in combination with detailed modeling of the cluster mass distribution, the geometry of the images can be used to constrain Ω_m.

Here we concentrate on some of the weak lensing applications, for which we use 24 deg^2 of R_C-band survey data (16.4 deg^2 of CFHT, and 7.6 deg^2 of CTIO 4m data). We present early results of the measurement of the lensing signal by intervening large scale structure (cosmic shear) and a study of the dark matter halos of (field) galaxies, as well as their biasing properties. The data analysed so far do not cover complete patches, and therefore we limit the analysis to the individual pointings.

A detailed description of the data and weak lensing analysis will be provided in Hoekstra et al. (2001b). The results presented in Hoekstra et al. (2001b) indicate that the object analysis, and

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[1] http://www.astro.utoronto.ca/~gladders/RCS

the necessary corrections for observational distortions work well, which allows us to obtain accurate measurements of the weak lensing signal.

2 Measurement of Cosmic Shear

The weak distortions of the images of distant galaxies by intervening matter provide an important tool to study the projected mass distribution in the universe and constrain cosmological parameters (e.g., van Waerbeke et al. 2001). Compared to other studies, the RCS data are relatively shallow, resulting in a lower cosmic shear signal. However, the redshift distribution of the source galaxies, which is needed to interpret the results, is known fairly well. In addition, our data have been acquired using two different telescopes, but have been analysed uniformly. A detailed discussion of the analysis and the results is presented in Hoekstra et al. (2001b).

Comparison of the results from the two telescopes provides a useful test to check whether the various corrections for observational distortions have worked well. We find good agreement between the two measurements, and the combined top-hat smoothed variance is presented in the left panel of Figure 1 (16.4 deg^2 from CFHT and 7.6 deg^2 from CTIO). The signal-to-noise ratio of our measurements is very good, reaching ~ 6 at a radius of 2.5 arcminutes.

We use the photometric redshift distribution inferred from the Hubble Deep Field North and South to compare the observed lensing signal to CDM predictions. This redshift distribution works well, as was demonstrated by Hoekstra, Franx & Kuijken (2000) for the $z = 0.83$ cluster of galaxies MS 1054-03. The right panel in Figure 1 shows the inferred likelihood contours for a ΛCDM cosmology, with $h = 0.7$. For an $\Omega_m = 0.3$ flat model we obtain $\sigma_8 = 0.81^{+0.14}_{-0.19}$ (95% confidence), in good agreement with the measurements of van Waerbeke et al. (2001).
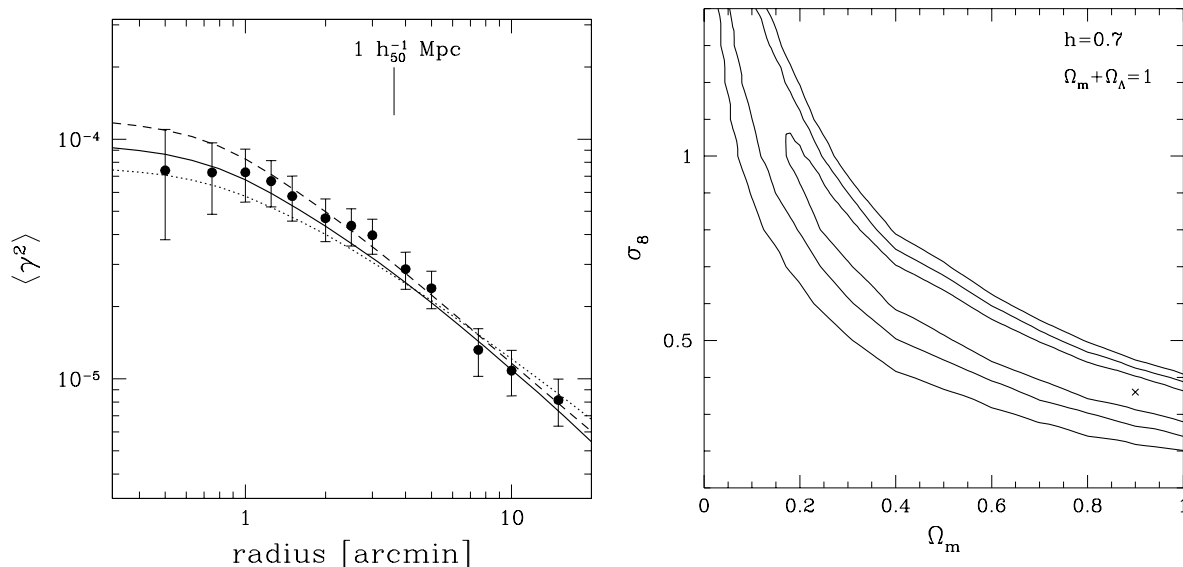

Figure 1: *left panel*: Measurement of the top-hat smoothed variance (excess variance caused by lensing by large scale structure) using galaxies with $20 < R_C < 24$. The data consist of 16.4 deg^2 of CFHT data and 7.6 deg^2 of CTIO data. The drawn lines correspond to the expected signals for a SCDM (solid line), OCDM (dashed line), and ΛCDM (dotted line) models, using $h = 0.7$. The errorbars are estimated from a large number of realisations of the data set where the orientations of the galaxies were randomized. Note that the points at various scales are strongly correlated. Under the assumption that the lensing structures are halfway between the observer and the sources, a scale of 1 h_{50}^{-1} Mpc is indicated. *right panel*: Likelihood contours as a function of Ω_m and σ_8, inferred from the analysis of the top-hat smoothed variance. The contours have been computed by comparing the measurements to CDM models with $n = 1$, $h = 0.7$ and $\Omega_m + \Omega_\Lambda = 1$. The contours indicate the 68.3%, 95.4%, and 99.7% confidence limits on two parameters jointly. Additional constraints on $\Gamma \approx \Omega_m h$ favour lower values of Ω_m.

3   Galaxy-galaxy lensing

Weak lensing is also an important tool to study the dark matter halos of field (spiral) galaxies (e.g., Brainerd, Blandford, & Smail 1996; Fischer et al. 2000). Rotation curves of spiral galaxies have provided important evidence for the existence of dark matter halos, but are confined to the inner regions, as are strong lensing studies. The weak lensing signal, however, can be measured out to large projected distances, and it provides a powerful probe of the gravitational potential at large radii. Unfortunately, the lensing signal induced by an individual galaxy is too low to be detected, and one can only study the ensemble averaged signal around a large number of lenses.

The results presented here are based on 16.4 deg^2 of CFHT data. We use galaxies with $19.5 < R_C < 21$ as lenses, and galaxies with $21.5 < R_C < 24$ as sources which are used to measure the lensing signal. This selection yields a sample of 36226 lenses and $\sim 6 \times 10^5$ sources. The redshift distribution of the lenses is known spectroscopically from the CNOC2 field galaxy redshift survey (e.g., Yee et al. 2000), and for the source redshift distribution we again use the photmetric redshift distribution from the HDF North and South. The adopted redshift distributions give a median redshift $z = 0.35$ for the lens galaxies, and $z = 0.53$ for the source galaxies.

The ensemble averaged tangential distortion around galaxies with $19.5 < R_C < 21$ is presented in the left panel of Figure 2. The solid line corresponds to the best fit SIS model, for which we find an Einstein radius $r_E = 0.184 \pm 0.011$ arcsec.

A better way to study the lensing signal is to compare the predicted shear (both components) from a parametrized mass model to the data. We use the truncated halo model from Schneider & Rix (1997). The results are presented in the right panel of Figure 2. With the adopted redshift distribution we obtain $\langle \sigma^2 \rangle^{1/2} = 111 \pm 5$ km/s. It turns out that the quoted value is close to that of an L_* galaxy, and our results are in fair agreement with other estimates.

In addition, for the first time, the average extent of the dark matter halo has been measured. Under the assumption that all halos have the same truncation parameter, we find a 99.7% confidence upper limit of $\langle s \rangle < 470 h^{-1}$ kpc. More realistic scaling relations for s give lower values for the physical
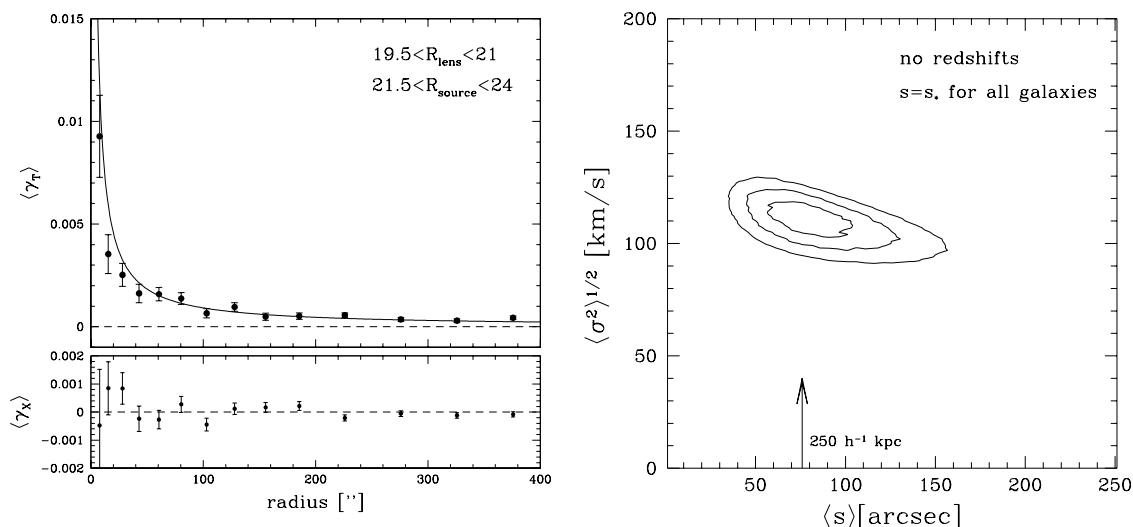

Figure 2: *left panel*: The ensemble averaged tangential distortion around galaxies with $19.5 < R_C < 21$. The solid line corresponds to the best fit SIS model, for which we find an Einstein radius $r_E = 0.184 \pm 0.011$ arsec. The lower panel shows the average signal when the sources are rotated by $\pi/4$. No signal should be present if the signal in the upper panel is caused by lensing. *right panel*: Likelihood contours for the mass weighted velocity dispersion, and the average value of the truncation parameter s. We have also indicated the physical scale when s is the same for all galaxies. The contours indicate 68.3%, 95.4%, and 99.7% confidence limits on two parameters jointly. For the first time, we find good constraints on the extent of the dark matter halos around field galaxies.

scale of $\langle s \rangle$, and therefore the result presented here can be interpreted as a robust upper limit.

We note that the results indicate a steepening of the tangential shear profile at large radii (which we interpret as a truncation of the halo), and alternative theories of gravity, such as MOND need to reproduce this. A plausible description of lensing by MOND was put forward by Mortlock & Turner (2001), which suggests that the shear in MOND drops $\propto 1/r$. A preliminary analysis excludes this prediction at high confidence.

4 Measurement of galaxy biasing

The study of the correlation between the galaxy distribution and the dark matter distribution (i.e. galaxy biasing) can provide useful constraints on models of galaxy formation. Most current constraints come from dynamical measurements that probe relatively large scales ($\geq$ a few Mpc). Schneider (1998) proposed a method that provides the unique opportunity to study galaxy biasing as a function of scale using weak lensing. This has been studied in more detail by Van Waerbeke (1998) who concluded that the results depend only slightly on the assumed power spectrum of density fluctuations.

In the standard, deterministic linear bias theory, the galaxy density contrast δ_{g} is related to the mass density contrast δ as $\delta_{\mathrm{g}} = b\delta$. However, the biasing relation need not be deterministic, but might be stochastic. In this case the galaxy-mass cross-correlation coefficient r is less than 1. Hence, we allow for stochastic biasing, and include the parameter r.

We use the 16 deg^2 of CFHT imaging data, which allows us to measure the mass-galaxy cross-correlation and the galaxy auto-correlation function. Unfortunately the data do not allow a accurate measurement of the (dark) matter auto-correlation function. A measurement of all three correlation functions would enable us to determine both b and r as a function of scale. In a forthcoming paper we plan to use the results of van Waerbeke et al. (2001) who measured the mass autocorrelation function from deep imaging data.

Here we present the results based on RCS data only, which results in a measurement of b/r as
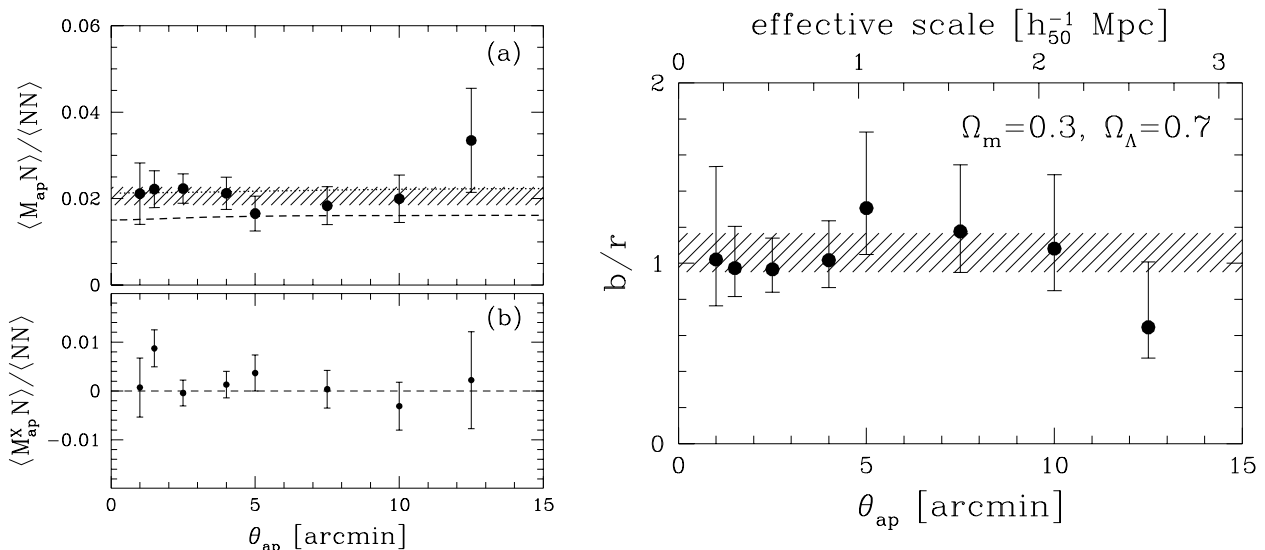

Figure 3: *left panel*: (a) The observed ratio of the galaxy-mass cross-correlation function $\langle M_{\mathrm{ap}}\mathcal{N} \rangle$ and the galaxy auto-correlation function $\langle \mathcal{N}^2 \rangle$. The dashed line indicates the prediction for an OCDM model with $b/r = 1$, and the dotted line corresponds to a ΛCDM model with $b/r = 1$. (b) The measured signal when the phase of the shear is increased by $\pi/2$, which should vanish if the signal in (a) is caused by lensing. *right panel* : Value of b/r as a function of scale, under the assumption $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. The upper axis indicates the physical scale corresponding probed. The results are consistent with a value of b/r that is constant with scale. For this cosmology we obtain $b/r = 1.05^{+0.12}_{-0.10}$ (indicated by the hatched region). Note that the points are slightly correlated.

a function of scale (for a detailed discussion see Hoekstra, Yee, & Gladders 2001a). The ratio of the galaxy-mass cross correlation and the $\langle M_{\mathrm{ap}}\mathcal{N}\rangle$ and the galaxy auto-correlation function $\langle\mathcal{N}^2\rangle$ is presented in Figure 3 (left panel), and the corresponding estimate of b/r (for a ΛCDM model) as a function of scale is shown in the right panel. The results are consistent with a value of b/r that is independent of scale, in agreement with the prediction of linear biasing. For the ΛCDM cosmology we obtain $b/r = 1.05^{+0.12}_{-0.10}$, suggesting that the light distribution traces the dark matter distribution quite well.

In the near future we will be able to measure the bias parameter on larger scales, and the accuracy of the estimates will improve significantly. With additional data this method will allow us to measure both b and r as a function of galaxy type, scale, and redshift.

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